

Domestic Solar Water Heater for Developing Countries

Final Presentation

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Outline

- **Project Overview**
- **Trip to Guatemala**
- **Design**
- **Cost analysis**
- **Future Plans & Goals**
- **Lessons Learned**
- **Acknowledgements**



Context & Background

- Current condition: Domestic hot water (DHW) is obtained *unsustainably* using **combustible fuel and/or electricity**.
 - Economics: not affordable
 - Environmental: non-renewable resource
 - Technical: minimal capabilities available for alternative methods
- Problem Statement: Develop a sustainable **low cost** solar water heater (SWH) system affordable to low incomes households in developing countries.

Current commercial devices range from \$400-\$1000.
Our goal is to develop a system for \$100.



**Schematic of Solar
Water Heater Principle**



Project Goals

Goals	<i>Design/ Performance</i>	<i>Economic/ Financial</i>
Minimum	<ul style="list-style-type: none">• Evaluate performance of solar water heater prototypes.• Design, build, and test a SWH to provide 100L of 40°C water by 4pm for a cost < \$100 using local materials & labor.• Ensure easy construction, repair and maintenance of unit.	<ul style="list-style-type: none">• Identify financial constraints of <i>target market</i>.• Offset <i>target markets'</i> financial constraints (e.g. carbon offsets or bank financing) to reduce per unit cost to <i>customers</i>.
Optimum	<ul style="list-style-type: none">• Meet minimum goals and be able to retain hot water overnight for early morning showers.	<ul style="list-style-type: none">• Implement financing options



Approach

as presented January 31, 2007

1. Select location for initial implementation

- ✓ • Contact local liaisons

2. Background research

- ✓ • Technical: solar thermal processes and engineering
- ✓ • Social/Cultural: current habits and usage of DHW*, needs, expectations
- ✓ • Economical: affordability and financing opportunities

3. Formulate conceptual matrix of prototype given community needs

- ✓ • Materials, local resources, available local technical labor, environment, safety, cost, installation, maintenance

4a. Design, build, test, and troubleshoot

- ✓ • Optimize design for energy efficiency and low cost
- Carbon offsets, liking to a financial institution...

4b. Formulate a framework for financial support

- ✓ • Carbon offsets, liking to a financial institution...

*DHW: Domestic Hot Water



Our Local Contact: AIDG

- Appropriate Infrastructure Development Group (AIDG)
 - Have worked on a SWH in the past
 - Too expensive (~\$400), need a low cost system
 - Have workshop that employs local people interested in engineering projects
 - 10 volunteer workers, all highly skilled with university and technical school backgrounds
 - Accounting to Electronics and Metal Casting



Our Local Contact: AIDG

Appropriate Infrastructure Development Group

Mission

“The Appropriate Infrastructure Development Group (AIDG) works to provide rural villages in **developing** countries with affordable and **environmentally** sound technologies that meet these needs. Through a combination of business incubation, education, training, and outreach, the AIDG helps individuals and communities **gain access to technology that will improve their lives**. Our model provides a novel approach to **sustainable development by empowering people with the physical tools and practical knowledge to solve infrastructure problems in their own communities.**”



Targeted community:

Urban Households of Xela, Guatemala

- Two main seasons in Quetzaltenango (Xela):
 - The rainy season (May through mid-November)
 - The dry season (December until May)
- At **2333 m** (7,655 ft) in elevation, Xela offers a temperate climate year-round temperatures at:
 - 15-20°C** (60-70°F) **during the day**
 - 4-10°C** (40-50°F) **at night**

Challenging for SWH!



AIDG- XelaTech's SWH



SWH = solar water heater

Design Selection

- Two main SWH systems:
 - **Active:** integrates pumps or rotary elements
 - **Too expensive**
 - **Passive:** uses natural circulation, gravity, &/or pressurized system
 - **Much cheaper!**
- *Is gravity sufficient or do we need to have a pressurized system?*
- Experiment: Set up a tank 10ft high (~ roof-to-living area height) and tested different showerheads.
 - Results: - Gravity provided sufficient pressure
 - Satisfactory **4L/min**



SWH = solar water heater



Preliminary Experiment: *Gravity Feed Test*



➡ Focus on Passive Systems



Possible Passive Designs

Natural Circulation

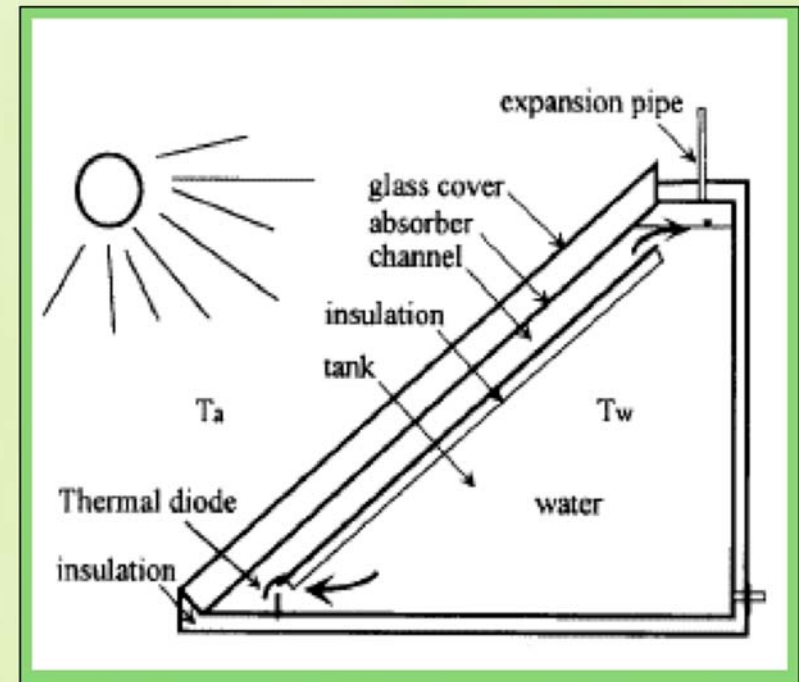
- Design options
 - Integrated storage collector SWH
 - (A) Thermal diode: non-pressurized
 - (B) Storage with baffles: non-pressurized
 - Separated storage collector SWH
 - (C) Thermosyphon: pressurized
- Build and test a design based on literature review with varying materials



SWH = solar water heater

(A) Thermal Diode

- Pro: Innovative thermal storage with separating plate; Diode
- Con: Building the multi-layered plate; Tank shape
- Thermal efficiencies ~ 50%
- Peak daytime 42°C
 - 5pm, ambient 35°C
- Low temperature 34°C
 - 5am, ambient 18°C
- Insulation
 - Plexiglass, Styrofoam boards

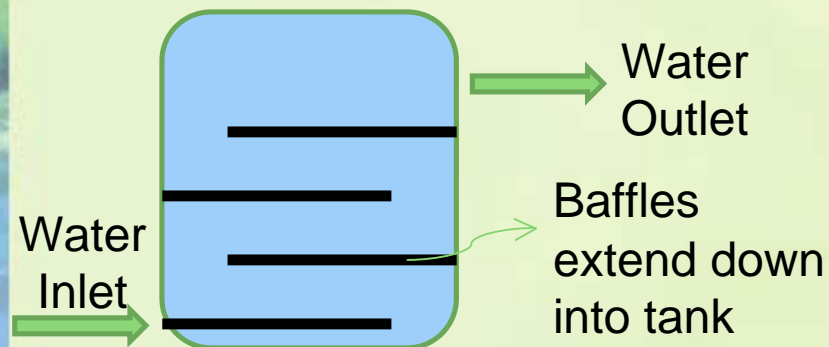


Mohamad, A.A. "Integrated solar collector-storage tank system with thermal diode." *Solar Energy* 61.3 (1997):211-218.

(B) Storage with Baffles

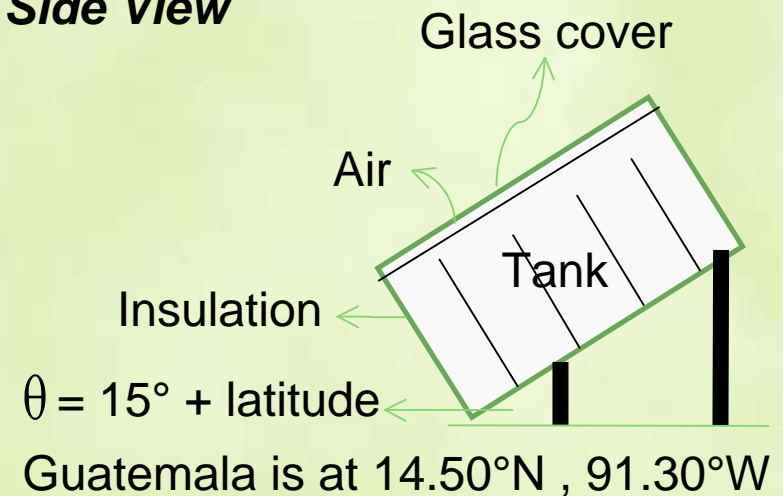
- Pro: Simple design; Number of parts
- Con:
 - Overnight storage mechanism
 - Water displacement mechanism

Top View



Tank is painted black to act as absorber

Side View

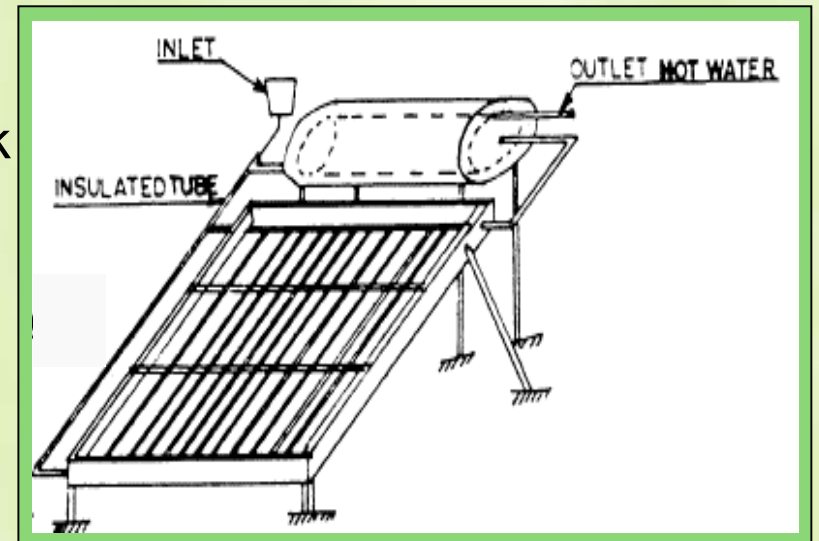


[1] Gadgil, A. "Economic, materials and performance constraints on the design of a solar DHW system for use in India." *Total Energy Research Institute* 1.1 (1987).

[2] Akuffo, F.O. and A. Jackson. "Simulation studies on a compact solar water heater in the Tropics." *Solar and Wind Technology* 5.3 (1987): 229-237.

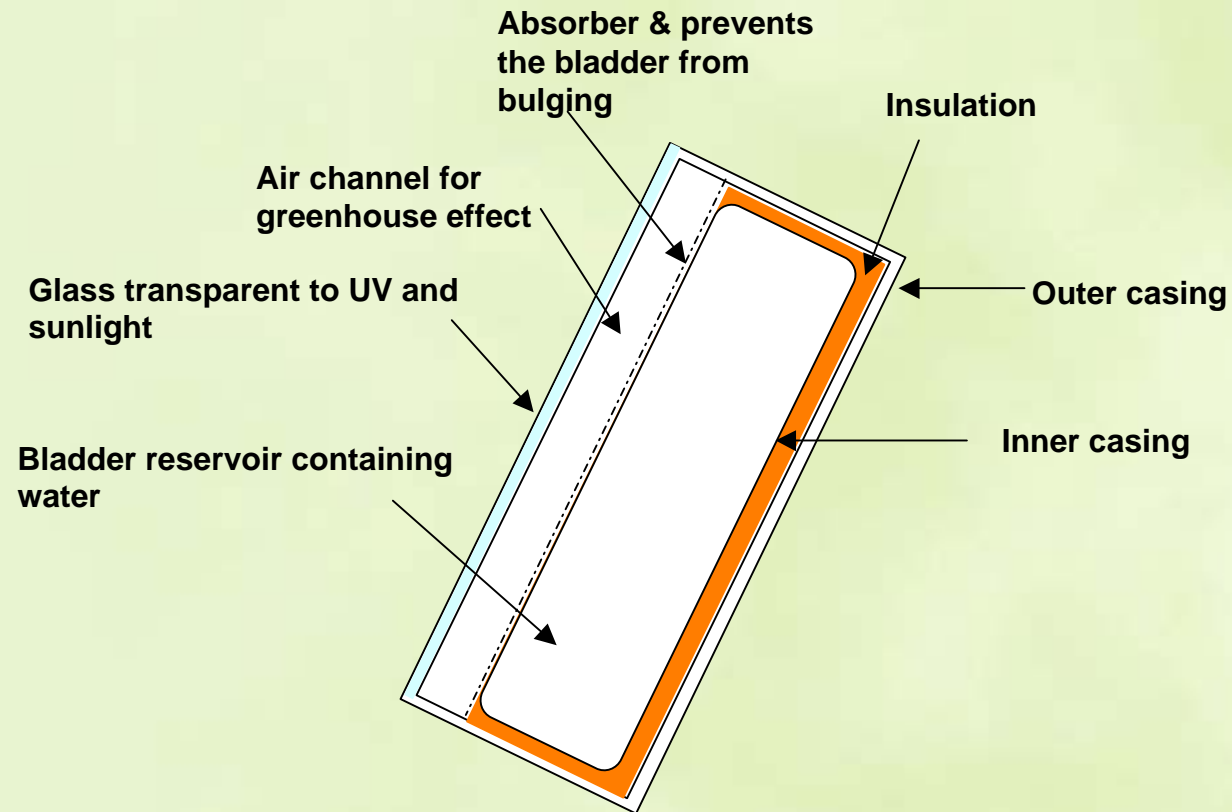
(C) Thermosyphon

- Pro: Separate units; cylindrical tank (pressure)
- Con: Cylindrical tank; Piping; Expensive
- Flat plate collector => 52% efficiency overall
 - *GS tube-Al sheet* vs. *Cu tube-Al sheet* vs. *Cu tube-Cu sheet*
- GS- Al collector ~\$170
- Avg temp 62°C (4pm) retained to 50.4°C (8am)
- Materials
 - Glass wool in inner drum of tank
 - Glass/plastic cover as heat trap



Nahar, N.M. "Capital cost and economic viability of thermosyphonic solar water heaters manufactured from alternate materials in India." *Renewable Energy* 26 (2002): 623-635.

Prototype Design



Trip to Quetzaltenango (Xela), Guatemala

Objective:

- Obtain on-the-ground information on material availability
 - Sustainable and cheap materials
- Assess the local demand for a solar hot water system
- Learn about their bathing/showering habits through informal conversations
- Explore Xela's building and manufacturing capacities by visiting hardware stores and compiling a list of local materials and prices
- Meet with AIDG members to:
 - Start survey
 - Discuss their current design
 - Visit their manufacturing facilities



End-User Survey

- Learn about urban households' hot water habits: consumption, methods, current costs...
- 16 questions in 4 different categories:
 - House characteristics (roof type, yard area, exposure to sun)
 - Household information (financial, size...)
 - Water distribution/source
 - Hot water usage and their bathing habits (hot shower? how often? In-line heaters?)
- Consulted Professor Isha Ray (ERG) on survey format and technique
- Currently applying for exemption from CPHS certification



Material Availability in Xela

US\$1 = 7.5Q (Quetzales)

Material	Price	Description detailed
Wood, plywood	4ftx8ftx1/4" 104Q 4ftx8ftx3/4" 154Q 4ftx8ftx1/2" 173Q	
Wire cage	2Q/yd	square wire mesh gage
	4 - 7Q	trapezoidal wire mesh gage
Garden Hose	122 Q for 75ft 86Q for 50ft	knitted reinforced 1/2" with brass coupling connection
Roof Tiles	6.55Q per ft	Wavy roof structure; undulated A-70 Galvanised 33" wide
Black Chalkboard Paint	87Q for a gallon	Brand: Protecto Dekativo negro
Glass	170Q (5mm thick) 104Q (3mm thick)	Glass window with 1.25m ² dimensions
High Density Polyethylene	4mil thick 0.2Q per ft 6mil thick 0.3Q per ft	PlasticLandia or PasticMundo
Vinyl	~10mil thick 0.4Q per ft	
In-line Shower Heater	132Q	Medium quality; Calentador Electrico Lorenzetti 110 Vol Maxi Ducha

Note: Prices were obtained by direct observation in the field, April 2007.



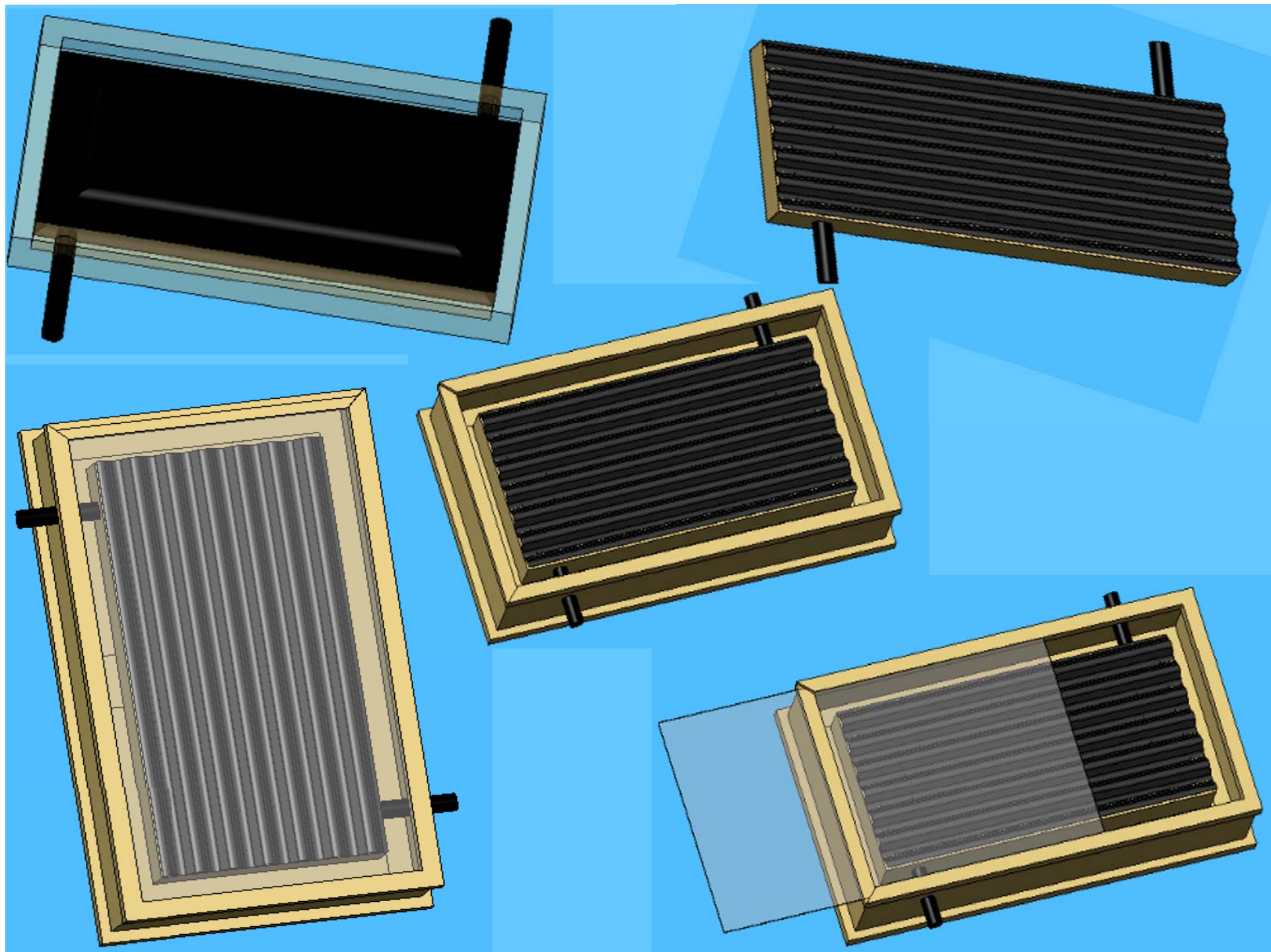


Prototype Materials

Prototype Component	Material	Attachment
Inner Case	Plywood (3/8" thick) and 2"x6"	Wood glue and screws
Outer Case	Plywood (3/8" thick), 2"x4", 2"x2", and 2"x6"	Wood glue and screws
Absorber	Wavy galvanized steel sheet metal and chicken wire	Screws and staples
Water Bladder	6mil, high density polyethylene (1mil=0.001in)	Heat sealed
Insulation	Packing peanuts and expanded polystyrene foam	Spray adhesive
Connections	Garden hose	"MacGyver" floss

Note: prototype materials were chosen based on Xela availability, cost effectiveness, and ease of testing. Wood is not intended to be used in final design; eventually use wavy galvanized steel and/or cement!





Building. . .Building. . . (and more Building)!



Still Building. . . .



Battling the Bulge!
(Who bought such cheap chicken wire?!)





Prototype Testing:

- Instrumentation

- Type T Thermocouples (9 total)

- ✓ Between bladder and inner case @ 10cm from the bottom, 10cm from the top, and center of inner case
 - ✓ Absorber surface
 - ✓ Ambient temperature

- Data Logger: collects temperature readings in specified time increments



Test Variables and Setup

Independent variables:

Absorber

- ☐ Chicken Wire vs. Wavy Galvanized Steel Sheet
- ☐ Insulation: packing peanuts for both prototypes
- ☐ **Control:** Chicken Wire

Insulation

- ☐ Packing peanuts
- ☐ Layers of packing peanuts and aluminum foil
- ☐ Fiberglass
- ☐ **Control:** Packing Peanuts

Testing to evaluate (dependent variables):

- Length of time to heat up 100L of water to 40°C
- Ability for system to retain heat overnight for early morning showers



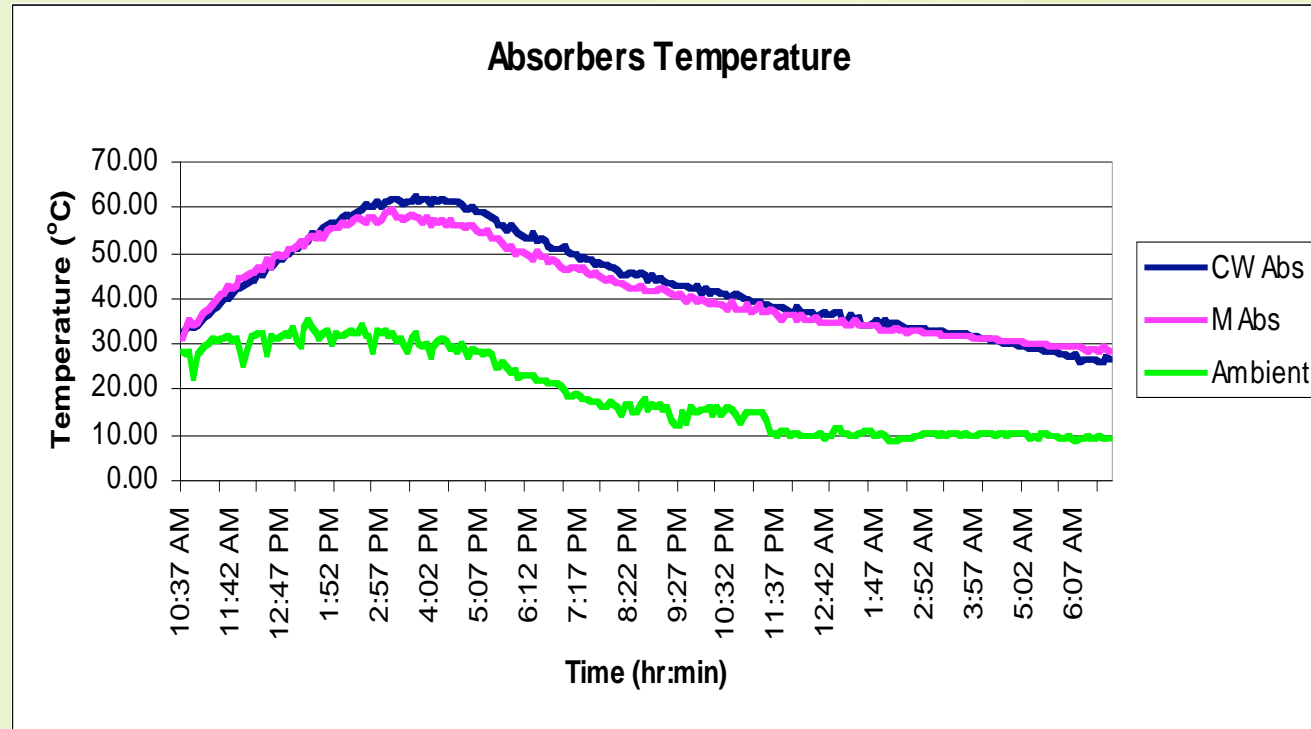
Test 1: Setup

- Prototypes angled at 48° from the horizontal facing South
- Prototypes were filled at 10:30am 4/28/07 and drained at 7:00am 4/29/07
- At end of experiment, prototypes were drained to determine water volume, early morning water temperatures, and thermal stratification
- Thermocouple readings were recorded every 5 minutes



Test 1: Absorber Analysis

Weather conditions: sunny with light, thin cloud cover



CW: prototype with chicken wire absorber



M: prototype with metal absorber

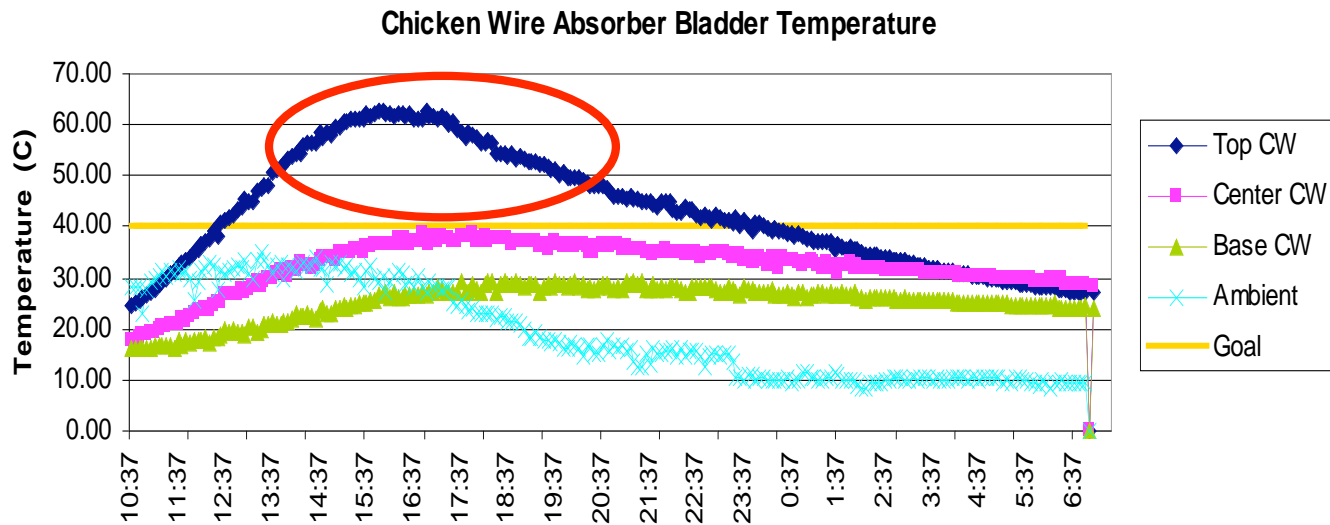


Test 1: Absorber Comparison

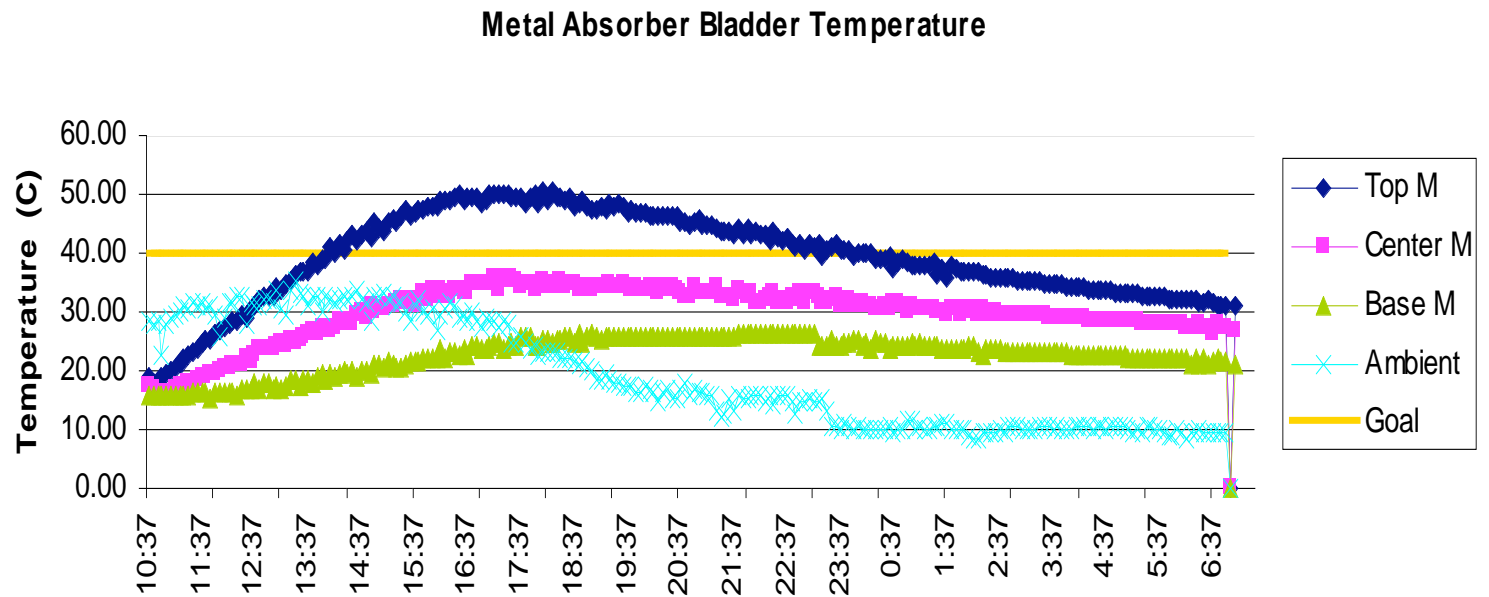
	Wavy Galvanized Steel Sheet Absorber	Chicken Wire Absorber
PROS	Structural support More resistant to deflection	Extremely low cost
	Less labor intensive Easier to install and paint	
CONS	Uncertainty in air gaps between absorber and water bladder	Less structural support
		Labor intensive



Test 1: Bladder Analysis

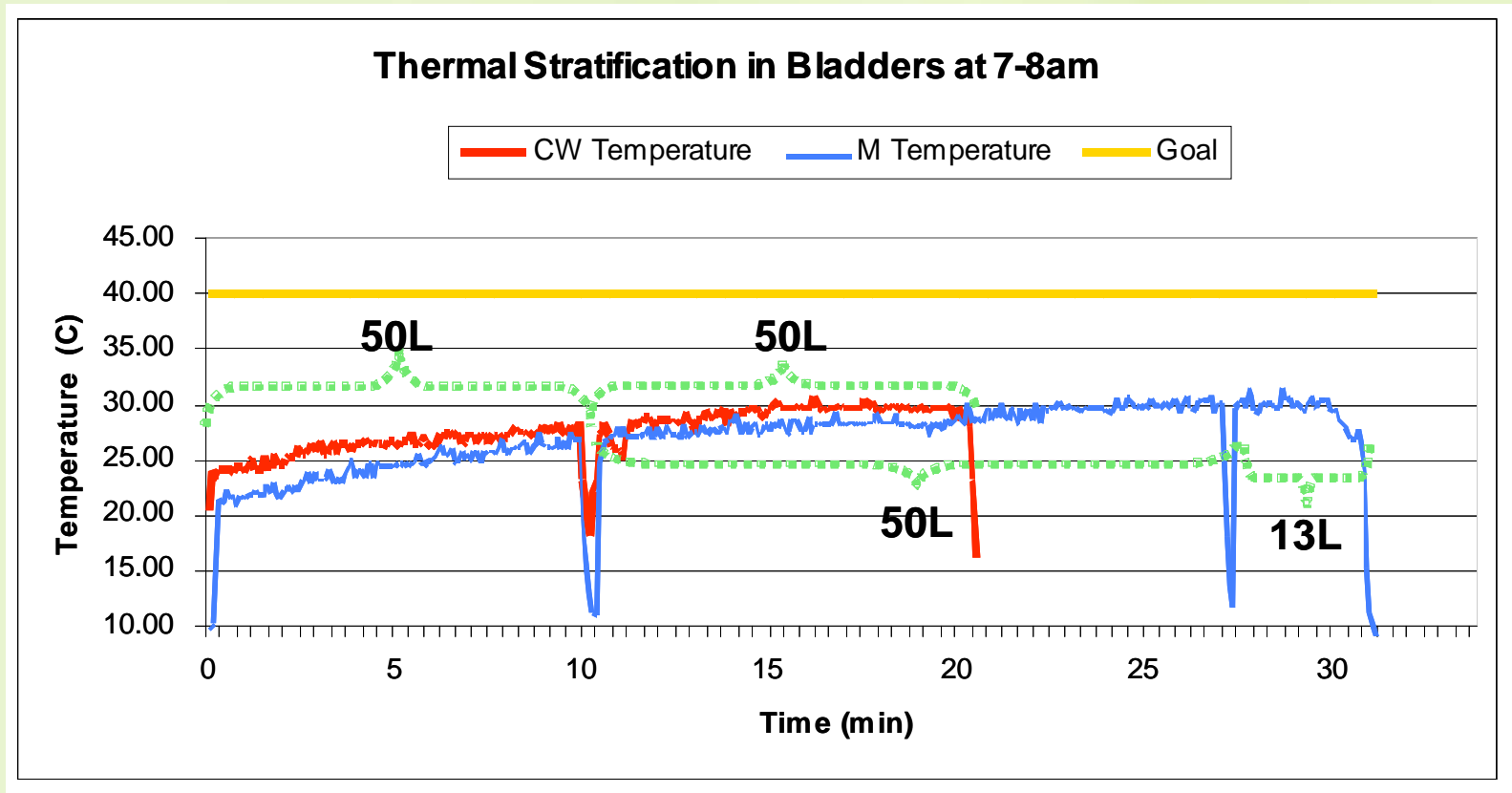


Note: Slow leak in CW prototype inlet lowered the volume of water in the bladder => Higher stratification temperatures were measured.



Test 1: Draining Water

Weather conditions: Morning fog with an ambient temperature of 10°C



CW: chicken wire absorber prototype had 100L water after leak & T varied from 24-30°C

M: metal absorber prototype had 113L in bladder & T varied from 21-30°C



Test 1: Results

AVERAGE VALUES	Maximum Temperature	Time from 10:30am to Heat up to 40C	Overnight Heat Loss from max temp time to 7am
CW Absorber	62 °C	3.5 hr	
M Absorber	59 °C	1 hr	
CW Bladder	62 °C*	5.25 hr	41 W/m ² (61W)
M Bladder	50 °C	3 hr	38 W/m ² (61)

*Due to slow leak, thermocouple at the top of the chicken wire prototype was in contact with higher position in the stratification compared to the metal prototype.

Based on heat loss calculations, estimated R-value for the metal prototype is R-0.17 (K.m²/W) and for the chicken wire prototype is R-0.19 (K.m²/W)



Test 1: Conclusions

- Chicken wire and wavy galvanized steel sheet are comparable in performance as absorbers
 - Can not make direct comparisons of data due to leak in chicken wire prototype inlet
 - Decreased water volume, shifted water stratification, and overestimated temperatures due to the top thermocouple being exposed to air
 - Necessitates more testing to determine which loses heat faster
- Temperature gain: About 40-50L of water was at or above 40°C by 5pm in both systems, which was retained to 30°C by 7am the next morning after 10°C night
 - Large heat loss due to deflection of water bladder/absorber onto glass: decreasing air space between absorber and glass
 - Necessitates improvements in absorber strength to avoid deflection
- Stratification existed throughout day and night, decreasing due to ambient losses
- Initial water bladder testing successful!
 - Necessitates further lifetime analyses of sealing techniques



Cost Goals

Develop a design that can be mass produced and sold in Guatemala for \$100

...Production costs must be \$30 or less (remaining \$70 for business management expenses, marketing, etc.)

...\$30 Production costs in Guatemala are equivalent to \$60 mass production costs in the U.S.

... \$60 mass produced in U.S. is roughly equal to **\$200 hand-made in U.S.**



Material Cost Per Unit

Item	Amount of material	Cost for Chicken Wire SWH (US\$)	Cost for Metal SWH (US\$)
Ply Wood (base inner case)	1 board	6.37	6.37
Ply Wood (base, outer case)	2 boards	12.74	12.74
Ply Wood (sides)	0.5 board	5.475	5.475
Wood (2 x 4)	1 board	2	2
Wood (2 x 2)	2.5 lengths	4.375	4.375
Wood (2 x 6)	2 boards	8	8
Corner Supports	1/8 board	0.875	0.875
Wavy Sheet Metal	1 sheet		9.48
Screws	0.5 box	3.5	3.5
High Density Polyethylene (water bladder)		7.45	7.45
Garden Hose		15	15
Glass		93	93
Chicken Wire	1/5 of roll	1.4	
Studs	1 box per unit	2.38	2.38
Chalk Board Paint	0.5 can	2.5	2.5
Expanded Polystyrene Foam	9 blocks per unit	50	50
Packing Peanuts	10.6 cu. ft per unit	9	9
Total		\$224.065	\$232.145



Annual Household Energy Savings from Solar Water Heating

	Typical Guatemalan Household: Without Solar Water Heater	Typical Guatemalan Household: With Solar Water Heater
Estimated average shower length (minutes per day)	7.5	7.5
Average kW usage from shower head ¹	6	6
Estimated average number of heated showers per day	3	3
Average number of in-line showers per day ²	3	1.5
Total minutes of in-line heater use per day	22.5	11.25
Total daily kWh used in showering	2.25	1.13
Total annual kWh used in showering	821.25	410.63
Total annual kWh reduced by solar water heater use		410.63
Annual Savings (in Guatemalan Quetzales) ³		205.31
Annual Savings (US\$) ⁴		\$27.38
¹ assumes that a solar water heater will offset half the use of an in-line heater		
² based on average power of commonly available in-line water heaters		
³ AIDG estimates that electricity in urban areas of Guatemala averages 0.5 Quetzales per kWh		
⁴ assumes exchange rate of 7.5 Quetzales per U.S. dollar		



Cost of Conserved Energy

Assume:

- no maintenance cost over 5 year life*
- 6% social discount rate*
- add 10% electricity use to account for transmission losses and government subsidies*

Net Present Cost = \$100

Annual Levelized Cost = \$25.64 (192.3 Q)

Annual Energy Savings = 451.63 kWh/year

Cost of Conserved Energy = 0.42Q per kWh

...less than current energy costs (0.5 Q per kWh)

...with 10 year life and same cost: 0.21 Q per kWh



Microfinancing

- Goal: Understand the potential benefits of microfinancing institutions (MFIs) partnership
- Exploring partnerships with MFIs in Guatemala
 - Partnership could improve distribution by lengthening payback period and expanding marketing opportunities
- Contacts with Namaste International



Carbon Offsets

- Exploring the sale of carbon offsets from avoided electricity use
 - Contact with Climate Care, Inc.
- Obstacles: Uncertain fossil fuel generation in Guatemala's energy mix
- Estimated offset price: \$3-20/ton CO₂
 - 0.067 tons CO₂ savings
- Estimated value/unit: \$0.50-\$3.15



Project Future Plans

- Field testing in Guatemala summer 2007
 - Testing for durability, ease of use, and production
 - Modifying for more available/sustainable materials & improved performance
- Secure financing options
 - Work with AIDG contacts to offer micro-financing options, specifically for women in Xela, Guatemala
 - Investigate carbon offsets
- Further modifications
 - As AIDG expands to other parts of the developing world, the design will be modified accordingly to include locally available materials and meet unique needs of local end-users.
 - Replace wood with cement, wavy metal, and chicken wire



Lessons Learned

- Interdisciplinary nature of problem => need to work in parallel on
 - Cultural/social needs:
 - Surveys
 - Engineering design:
 - Building before determining ultimate design provides valuable learning experience
 - Economic sustainability:
 - Current energy resources and prices
- Travel early!



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Questions?!

